Direct Constraints of HI Cosmic Reionization from Lyman-α observations at z $\sim$ 5-6

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LBNL
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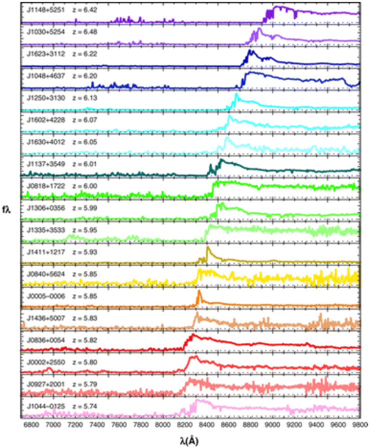
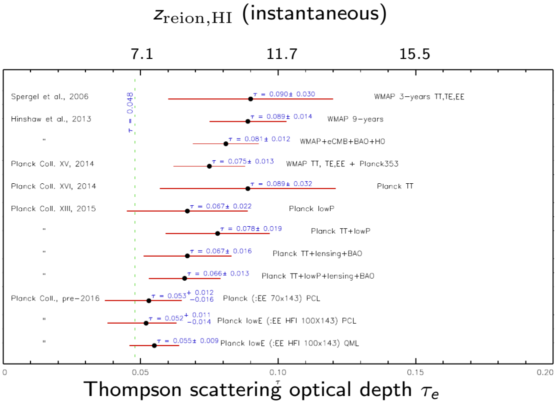
Outline

1. Reionization and the Thermal State of the Intergalactic Medium
2. Constraining HI Reionization from the $z \sim 5-6$ Ly-α Forest
3. Simulating Inhomogeneous Reionization
4. Take Away Messages

Empirical Constraints on Reionization



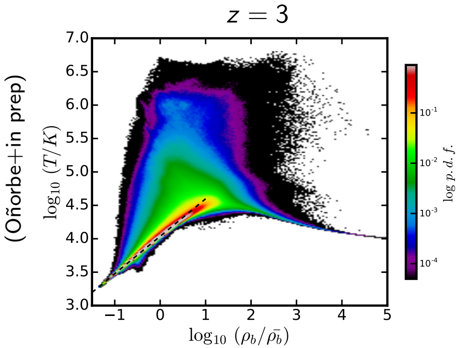
Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62

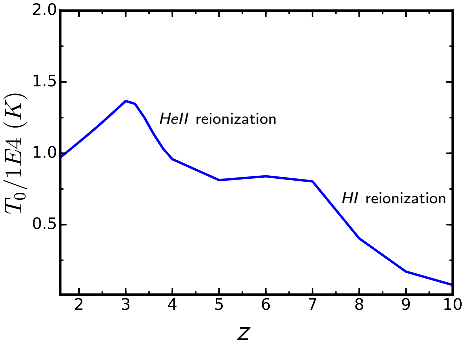


IGM transmission toward $z \sim 6$ QSOs and CMB optical depth provide only robust constraints on reionization

Reionization Sets the Thermal State of the IGM

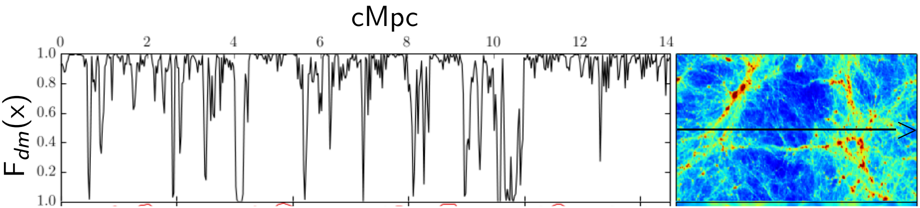
- Balance of photoheating and adiabatic cooling gives a $T - \Delta$ relationship: $T(\Delta) = T_0 \Delta^{\gamma - 1}$ (Hui & Gnedin, 1997)





1. Study the reionization history
2. Constrain the thermal injection from ionizing sources
3. $T_{\rm IGM}$ important for galaxy formation ($M_{\rm halo,min}$)

The Pressure Smoothing Scale of the IGM



If we could somehow probe the dark-matter directly
the Ly-α forest would look like this

(Kulkarni,JO+2015)

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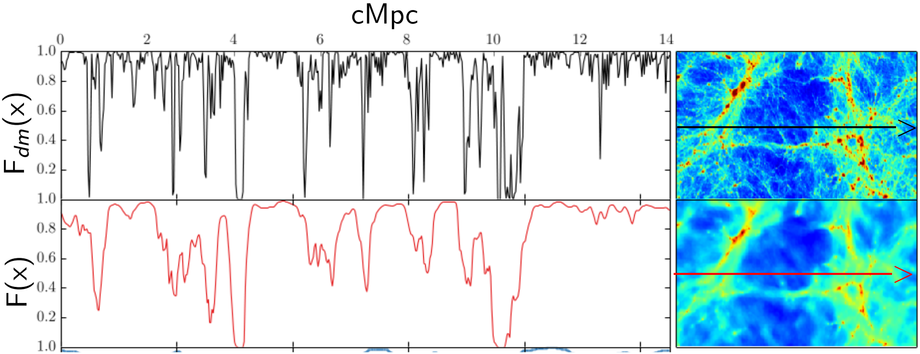

Pressure forces → baryon smoother than dark matter

(Kulkarni,JO+2015)

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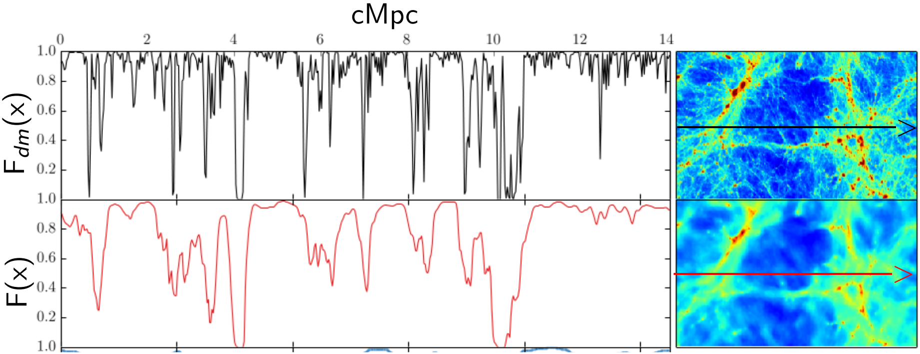


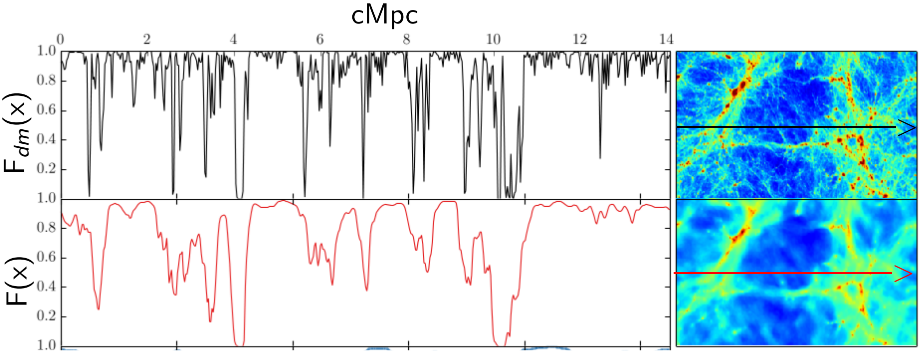
Pressure forces $\rightarrow$ baryon smoother than dark matter

Jeans sound-crossing time $\lambda_{Jeans}/c_s \sim t_H$ Hubble time,
IGM pressure scale depends on full thermal history

$$\lambda(z) = \int_z^{\infty} f[T(z')]dz'$$

(Kulkarni,JO+2015)

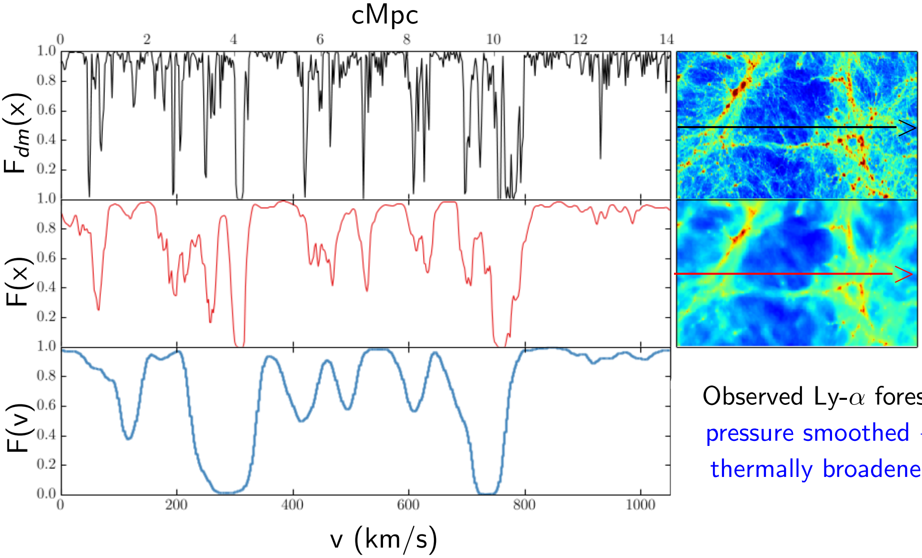
Thermal Doppler Broadening



Microscopic random motions of $T \sim 10^4$ K gas thermal Doppler broadens Lyα forest lines

(Kulkarni,JO+2015)

Cosmic Calorimetry with the Ly-α Forest

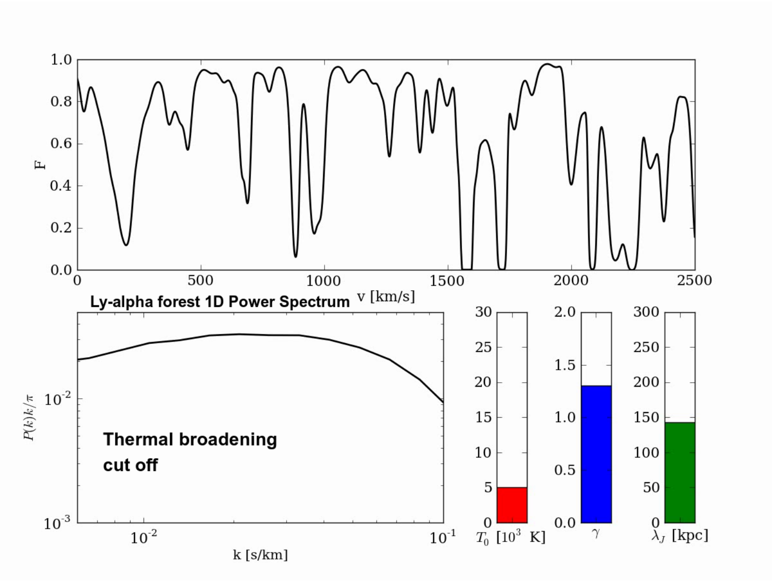


Observed Ly-α forest:
pressure smoothed +
thermally broadened

(Kulkarni,JO+2015)

Thermal Parameters Affect the Lyman-α Statistics

Credit video: A. Rorai



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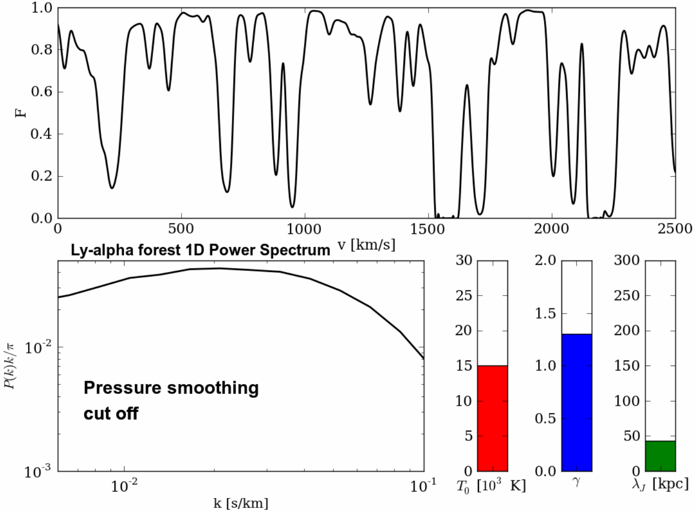


Simulating the Intergalactic Medium

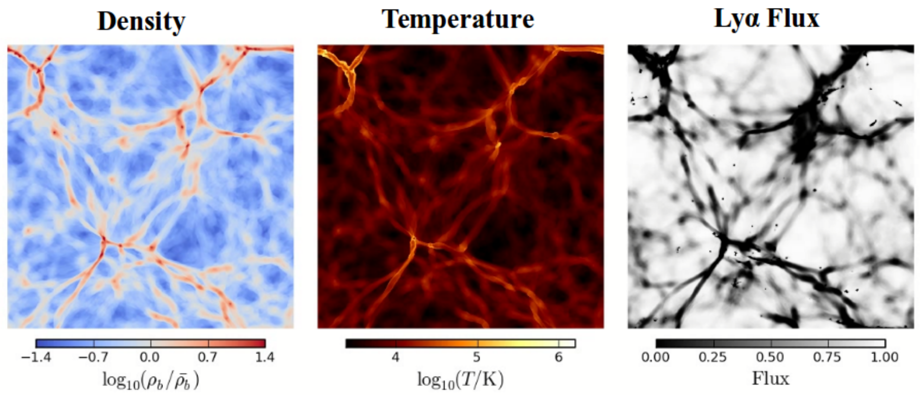
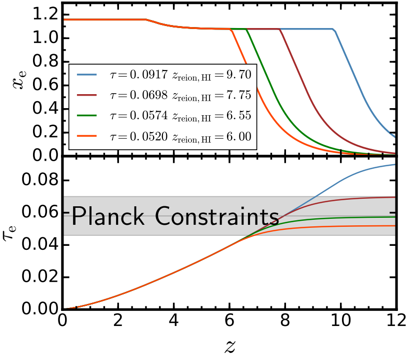


Image:Lukic

- Hydro + gravity, low density, CMB gives initial conditions
- Nyx massively parallel grid hydro code (Almgren+ 2013; Lukic+ 2015). A 2048^3 – 40 Mpc/h run costs $\sim 3 \times 10^5$ cpu-hrs
- Specific model of reionization (UV Background, Haardt & Madau 2012, Faucher-Giguere+2009)

Simulating Self-Consistent Reionization Histories



Oñorbe+2016

Hydro sims of reionization parameterized by

1) Ionization History: $Q_{HI}(z)$: z_{reion}, Δz
2) Amount of reionization heat injection: $\Delta T \Leftrightarrow$ spectral slope of reion. sources

Tables publicly available for your favorite hydro code

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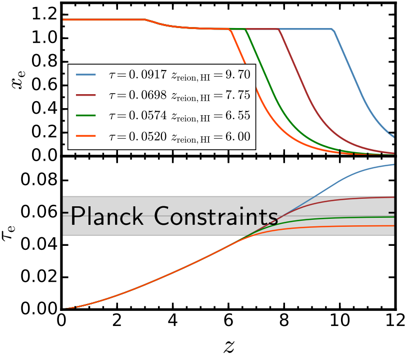

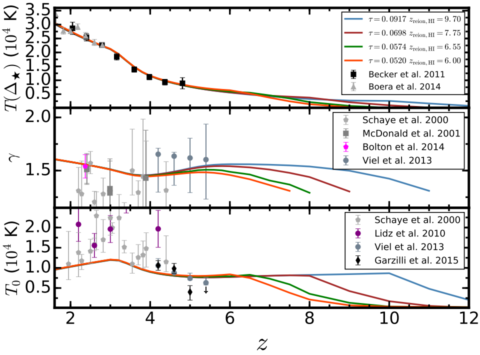

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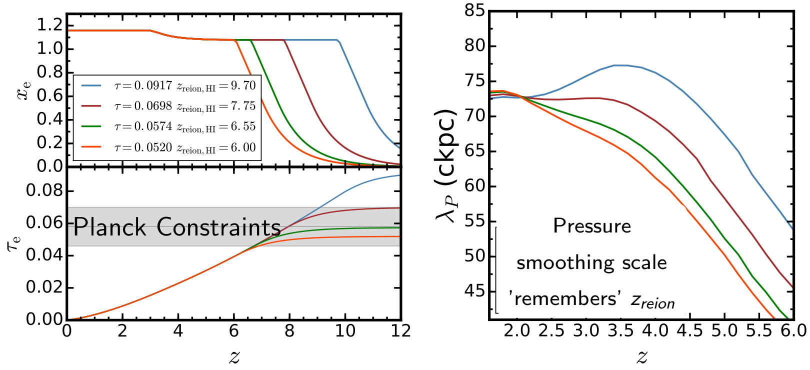

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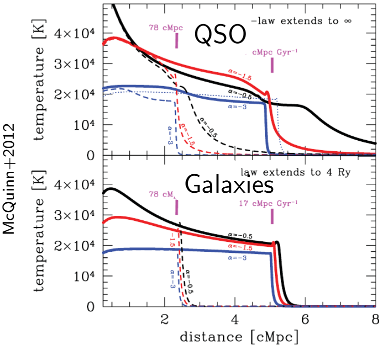

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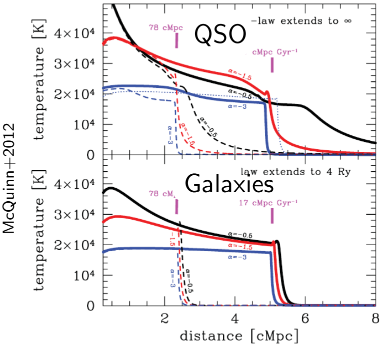

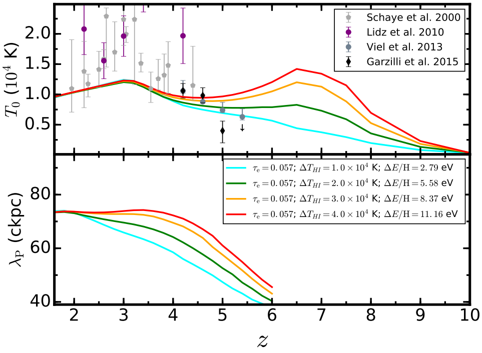

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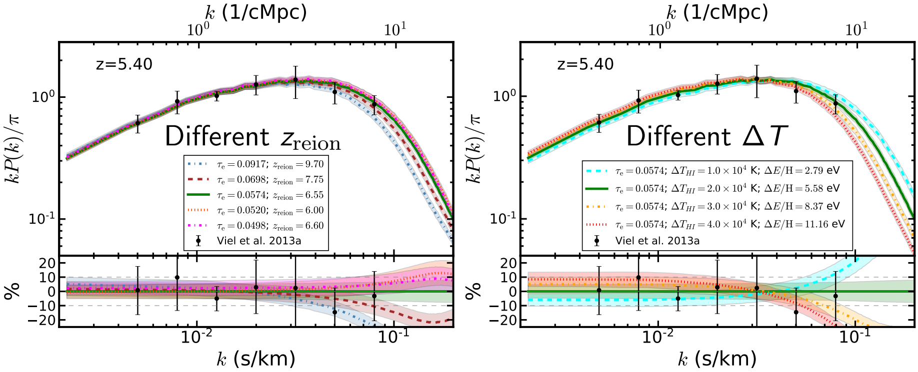
Constraining HI Reionization from $z = 5 - 6$ Lyman-α

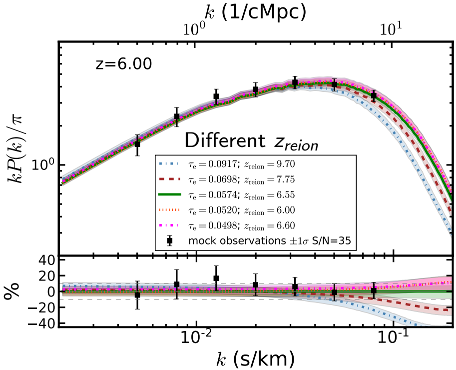
(Oñorbe+2017)

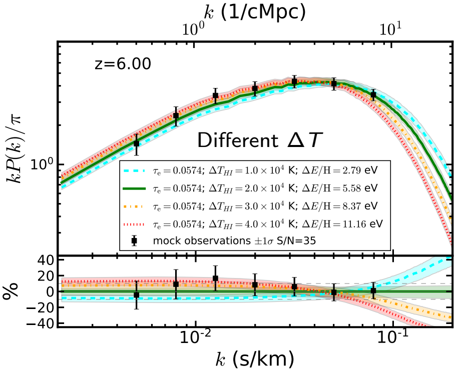


- Degeneracy between timing ($z_{\rm reion}$) and heat injection (ΔT)
- Degeneracy exists with Ly-α mean flux (easily solved)
- Measurements based on handful of QSOs, many more exist

(Factor > 5 @ $z > 6$, Pan-STARRS, DES, VIKING, SHELLQs, etc.)

At $z \sim 6$ Larger Differences in the IGM
(Oñorbe+2017)

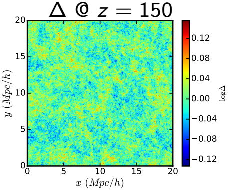


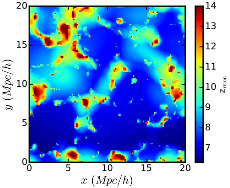


- Easier to distinguish between thermal histories

Simulating Inhomogeneous Reionization

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations (Oñorbe in prep)





Excursion set formalism:

(e.g. Davies+2016)

ICs + linear evolution $\Rightarrow$ $\mathrm{M}_{\mathrm{halo}}(z)$

$+\ M_{\mathrm{halo,min}} + \eta_{\mathrm{ion}} \Rightarrow z_{\mathrm{reion}}(\vec{x})$

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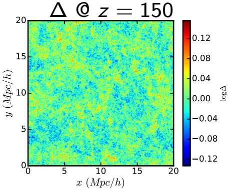

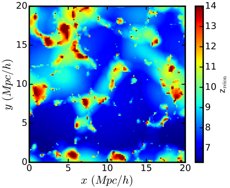

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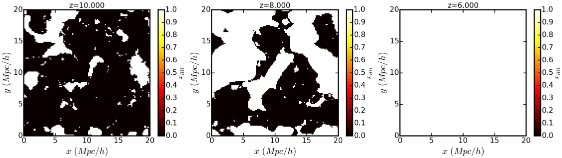
$z_{\rm reion}(\vec{x})$

$+$

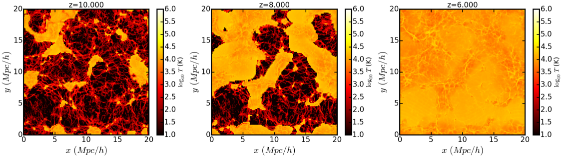
ΔT

(heat injected in 1 timestep)

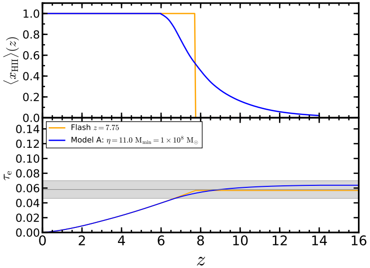
x_{HII}

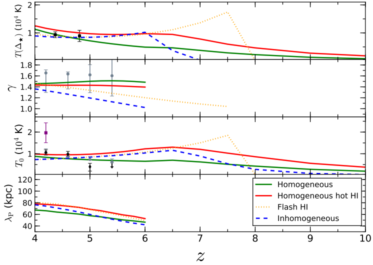


Temperature

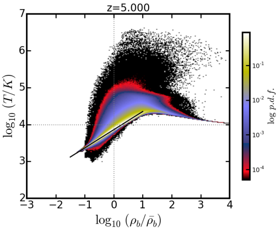


Differences Reionization Methods: Thermal history

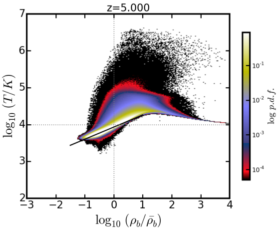




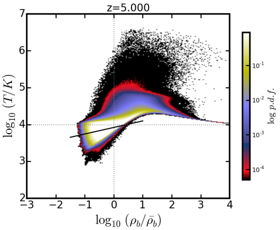
Homogeneous (UVB Table)



Flash (@ $z_{\rm reion}^{\rm median}$)

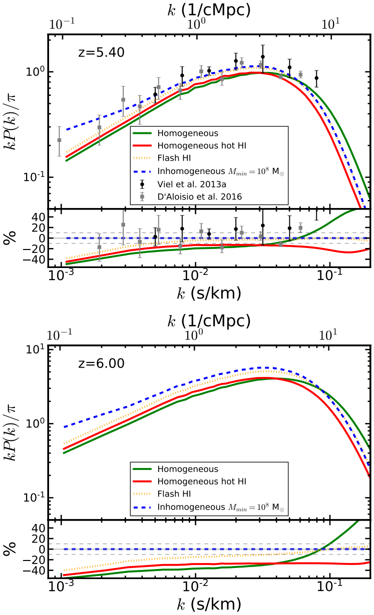


Inhomogeneous
($M_{\rm halo,min}=10^8\ M_\odot$)



Differences Reionization Methods: 1D Power spectrum

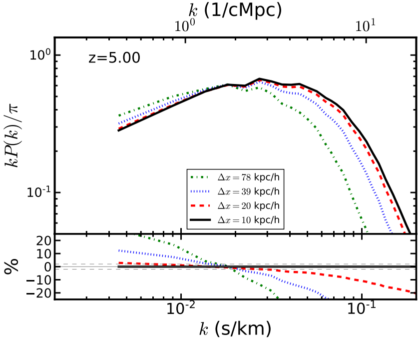
- Temperature fluctuations increase power at $k \lesssim 0.01 \Rightarrow$ Sensitive to $\Delta z_{\mathrm{reion}}$
- Flash and inhomogeneous model share the same cut-off shape
- Homogeneous (UVB table): Underestimates heat injection $\Rightarrow$ Cut-off and overall power.

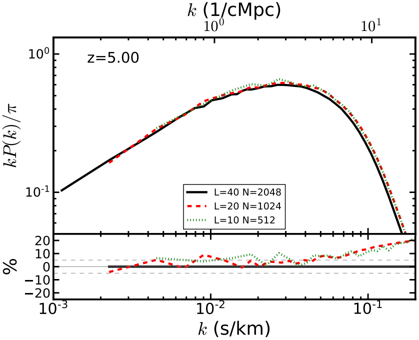


Take Away Messages

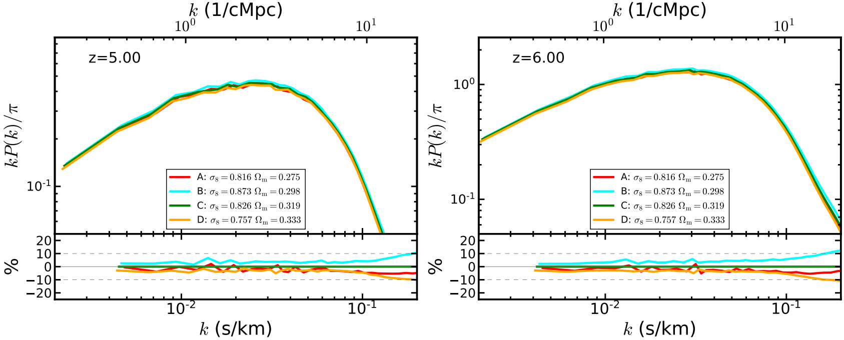
1. Reionization imprints a thermal record on the IGM detectable in the $z \sim 5-6$ Ly-α forest
2. The 1D flux power spectrum at $z \sim 5-6$ depends on the timing of reionization and its associated heat injection
3. Existing high-z QSO samples have enough precision to distinguish different models
4. Exploring the effect of inhomogeneous reionization with hydrodynamical simulations: cut-off of the 1D flux power spectrum not sensitive to temperature fluctuations.

Numerical Convergence

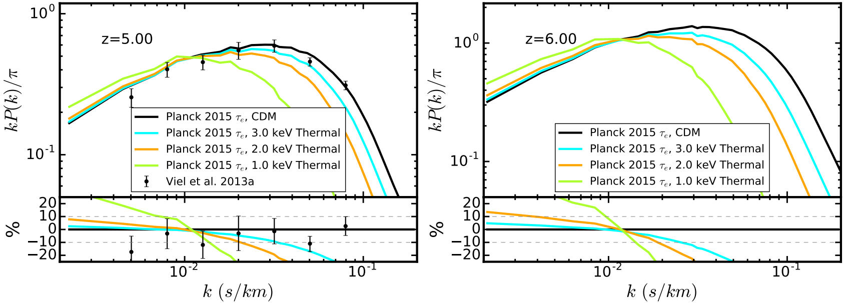




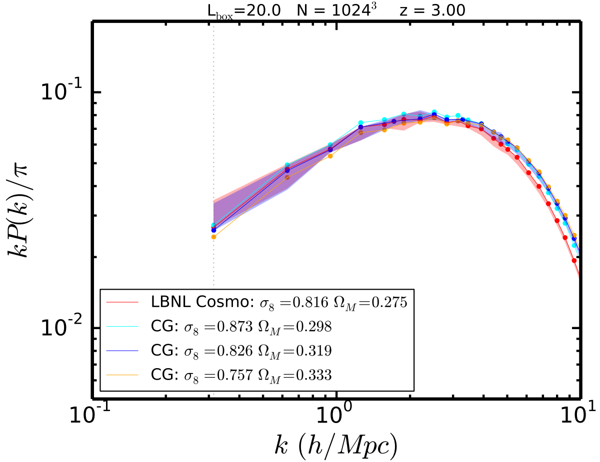
Degeneracy with Cosmological Parameters I



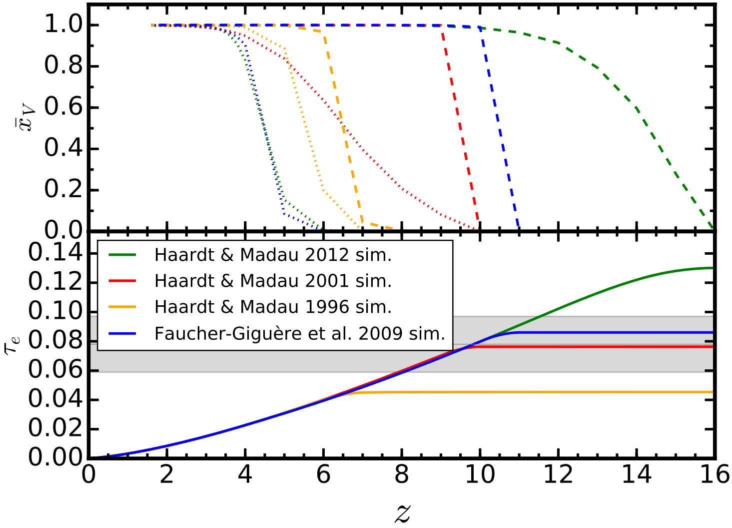
Degeneracy with Cosmological Parameters II: Warm Dark Matter



Cosmic Variance



Other UVB models I



Other UVB models II